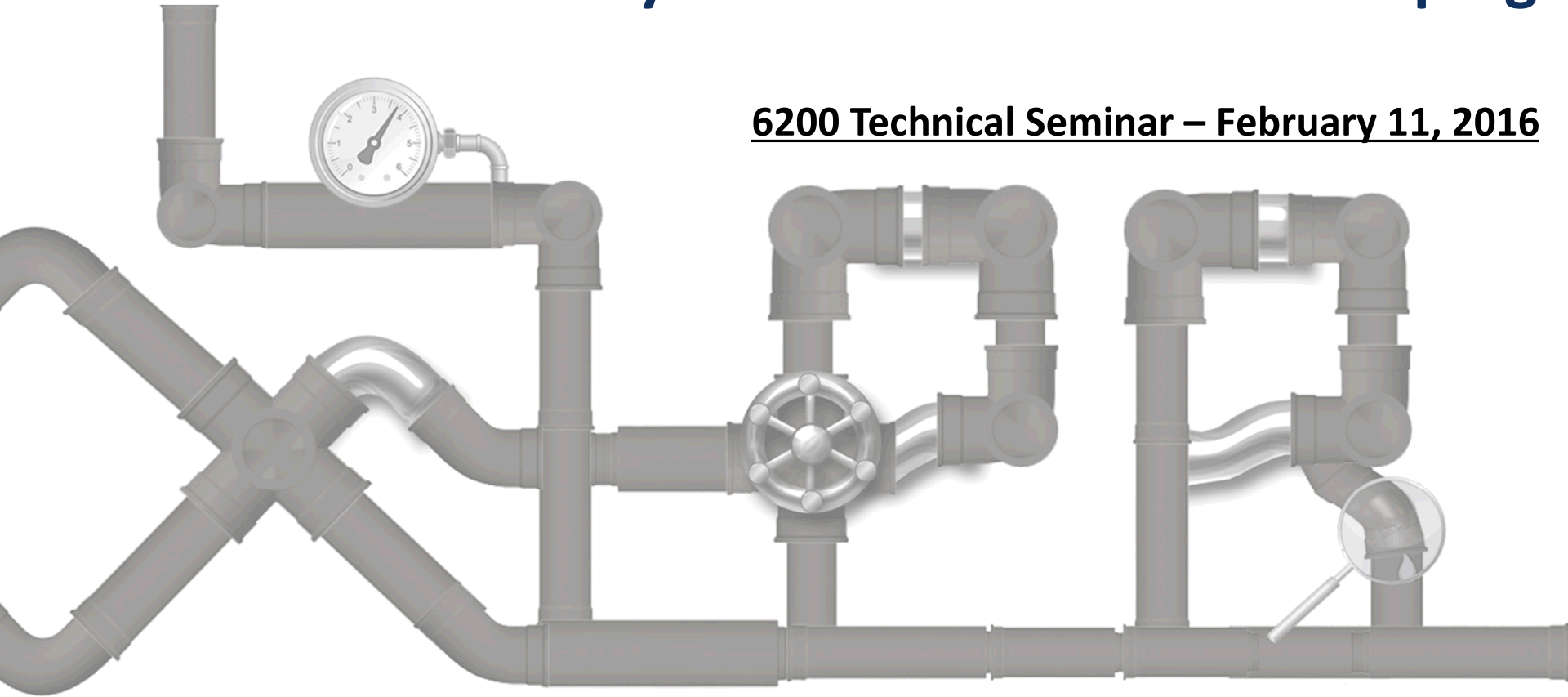


# xLPR - a Probabilistic Fracture Mechanics Approach to Weld Stability in Nuclear Power Plant Piping

SAND2016-1127PE

6200 Technical Seminar – February 11, 2016



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# Outline

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- **Why nuclear power?**
- **The LBB problem**
- **Probabilistic Framework**
- **Deterministic Models**
- **Some results**
- **Current Status**

# Acknowledgements

## Code Development Leads David Rudland – US NRC, Craig Harrington – EPRI



### Computational Group

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Steven Xu – Kinectrics

Doug Scarth – Kinectrics

Russ Cipolla – Aptech

Mike Hill – UC Davis

Steve Fyfitch – AREVA NP Inc.

Rick Olson – Battelle

Andrew Cox – Battelle

Lee Fredette – Battelle

Bruce Young – Battelle

Mark Dennis - EPRI

Carl Latiolais- EPRI

Thiago Seuaciuc-Osorio- EPRI

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Gary Stevens – U.S. NRC

#### **Matt Homiack – U.S. NRC**

Ashok Nana – AREVA NP Inc.

Nathan Palm – Westinghouse

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#### **Nate Leech – Demark**

### Program Integration Board

#### **Denny Weakland - Ironwood Consulting**

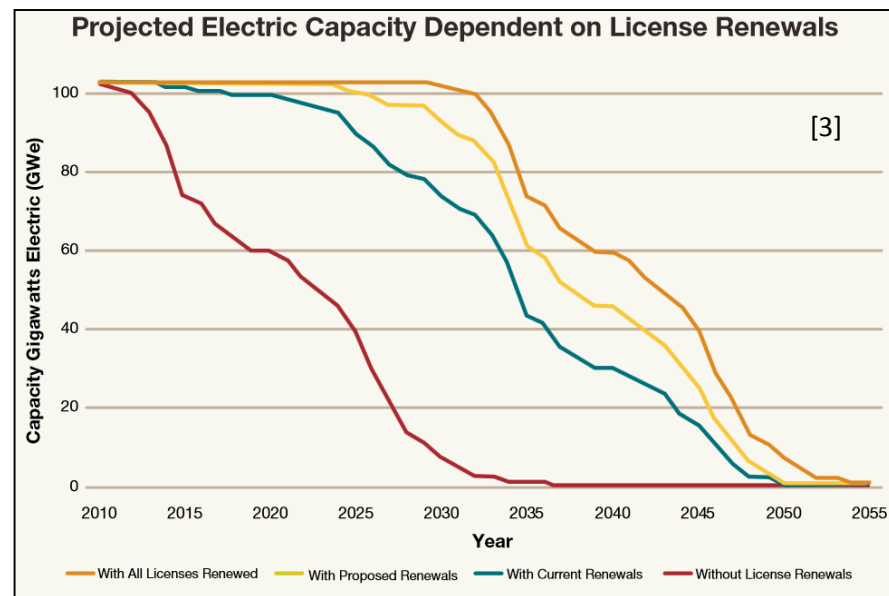
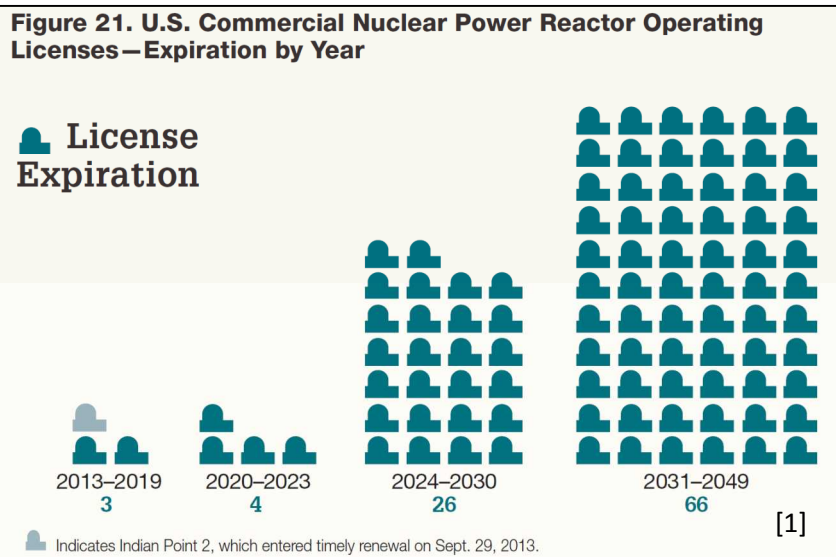
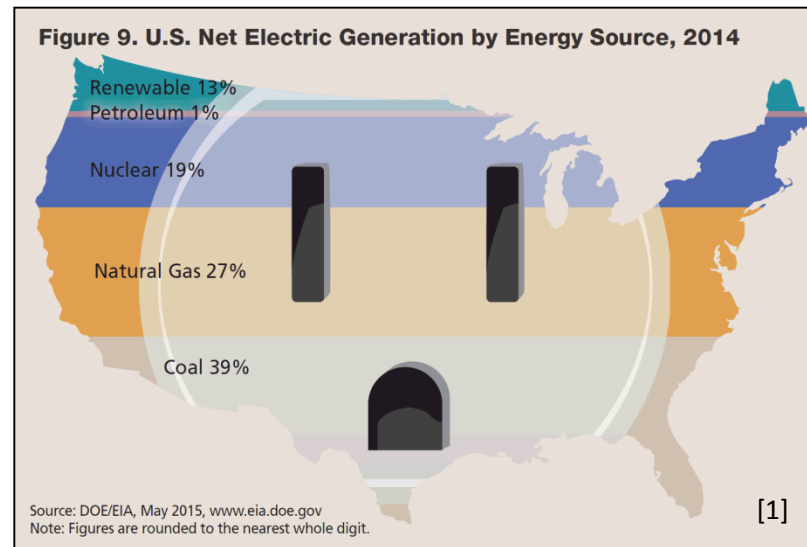
Bruce Bishop – Westinghouse

Rob Tregoning – U.S. NRC

Jay Collins – U.S. NRC

# Nuclear Power - Importance

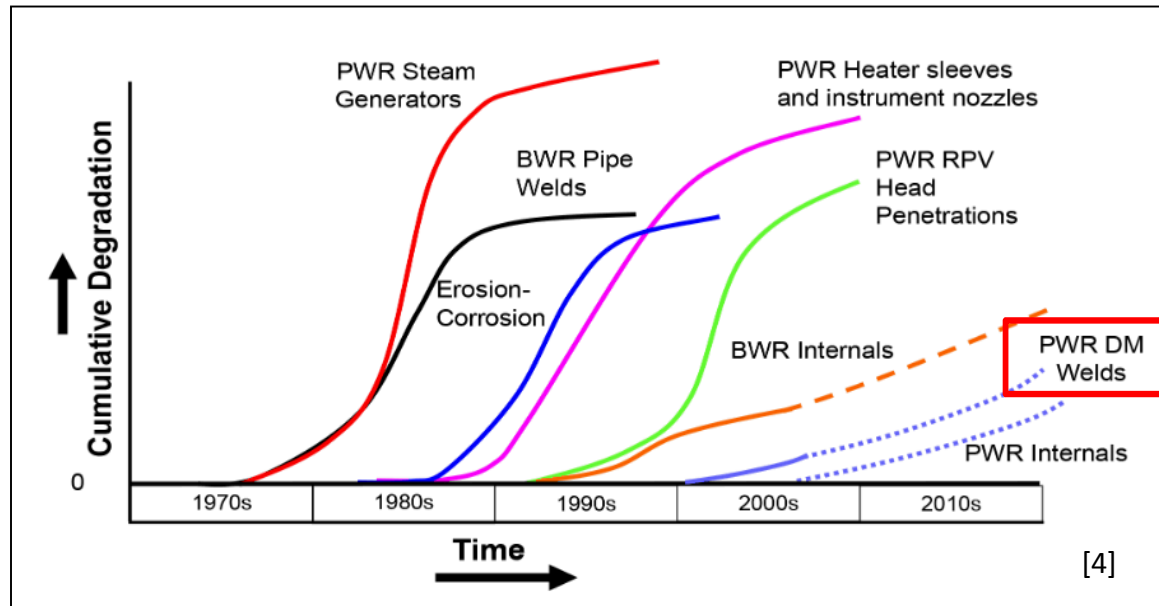
- 19% of electricity generated in the US<sup>[1]</sup>
- 63% of emissions-free electricity<sup>[2]</sup>
- Licenses will be expiring; power lost if not renewed
- New plants are costly



# Nuclear Power - Aging

- Many plants are old
- Materials aging and degradation have brought about some unique challenges

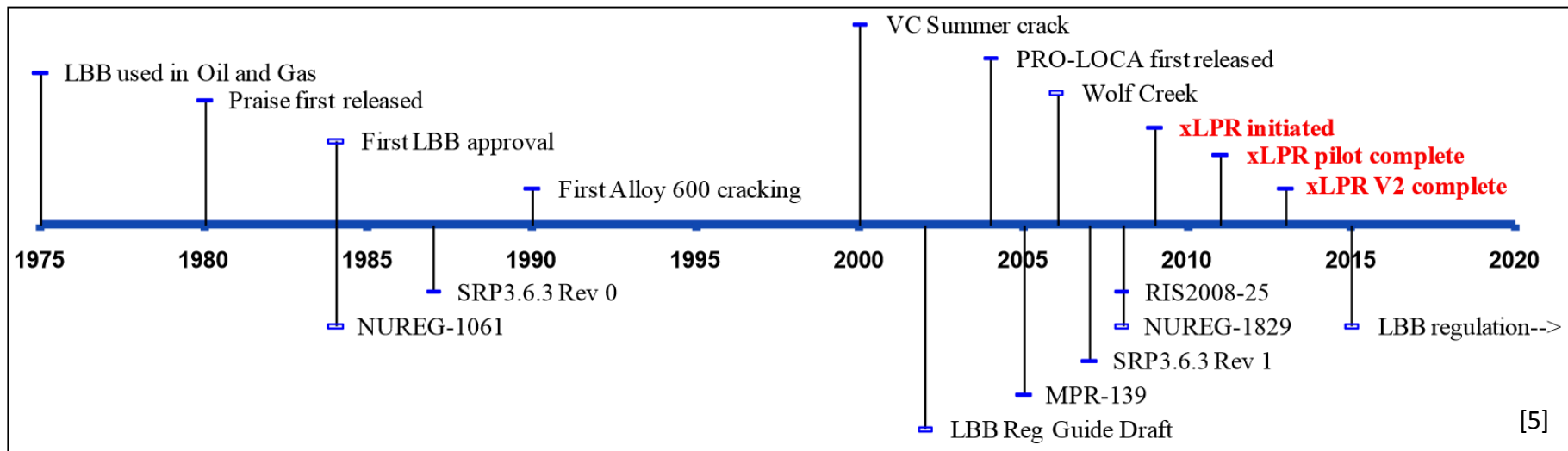
Figure 20. U.S. Commercial Nuclear Power Reactors—Years of Operation by the End of 2015 [1]



# Leak Before Break (LBB) Problem

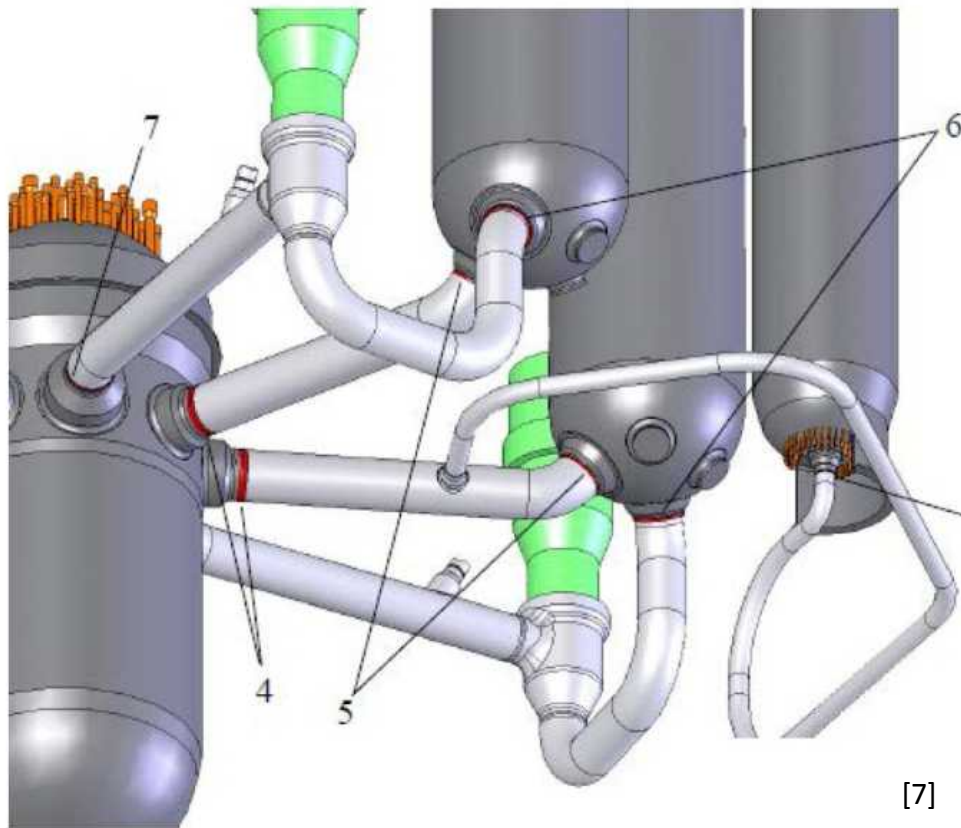
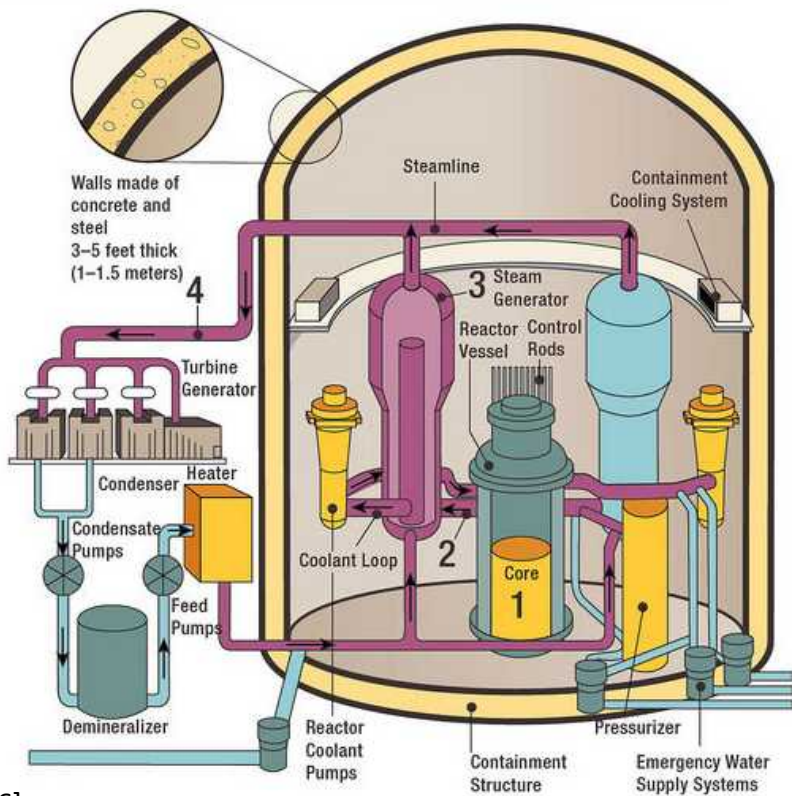
- 10CFR50 Appendix A General Design Criterion 4: local dynamic effects of piping rupture *may* be excluded from design basis
- LBB procedure used to justify approval of plant design excluding dynamic effects (no pipe whip restraints)
  - Assumes no active degradation mechanisms exist
  - However, after approval of LBB primary water stress corrosion cracking (PWSCC) was observed in many weld locations
- **eXtremely Low Probability of Rupture (xLPR)** ← Language in regulation

Probabilistic fracture mechanics tool that fully addresses and quantifies uncertainties and may be used to directly assess compliance with GDC-4



[5]

# Primary Water Reactor Welds

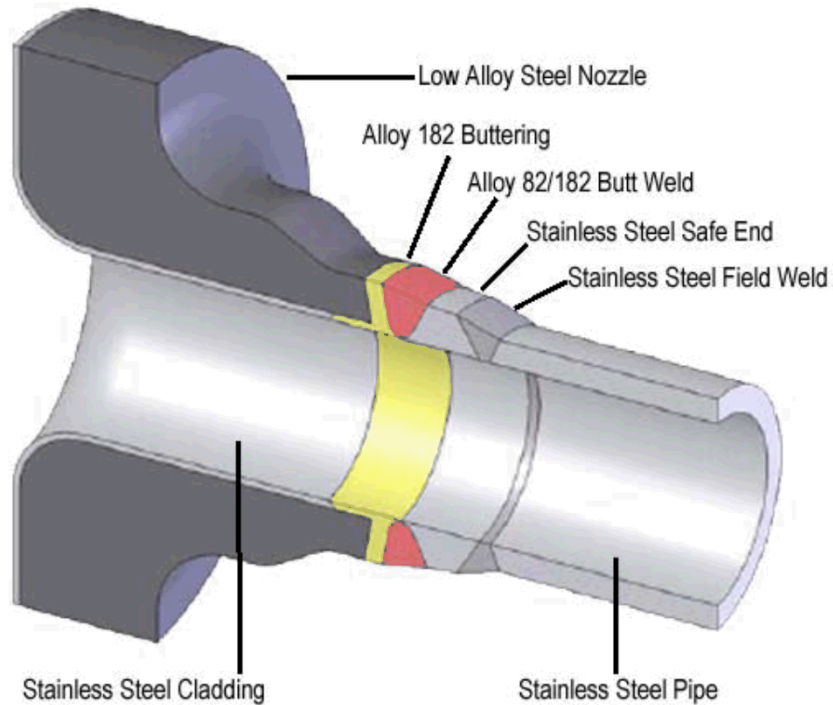


[6]

[7]

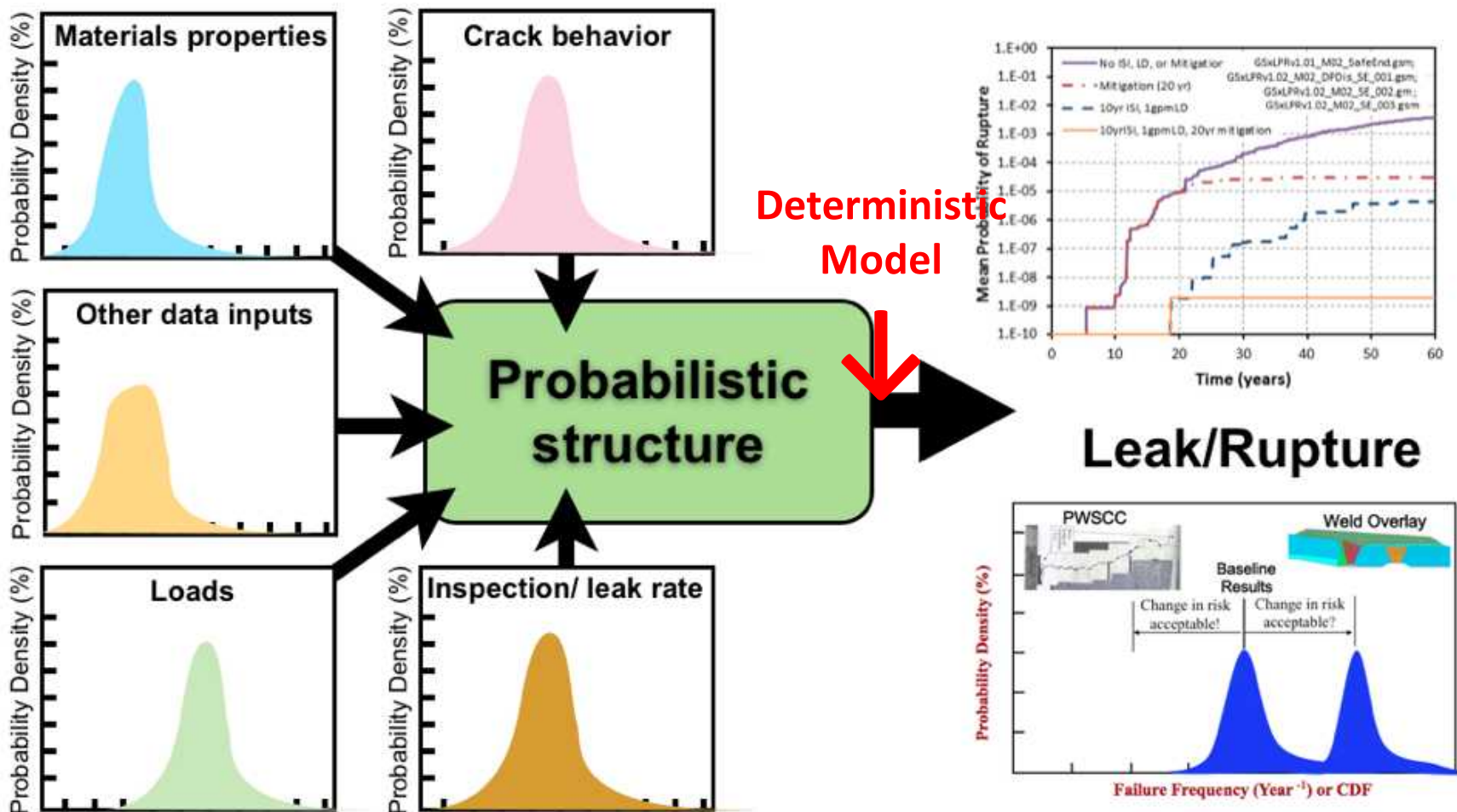
# Example Dissimilar Metal Weld

## Pressurizer Surge Nozzle



# Probabilistic Fracture Mechanics

- To demonstrate an extremely low probability of rupture a probabilistic approach is necessary

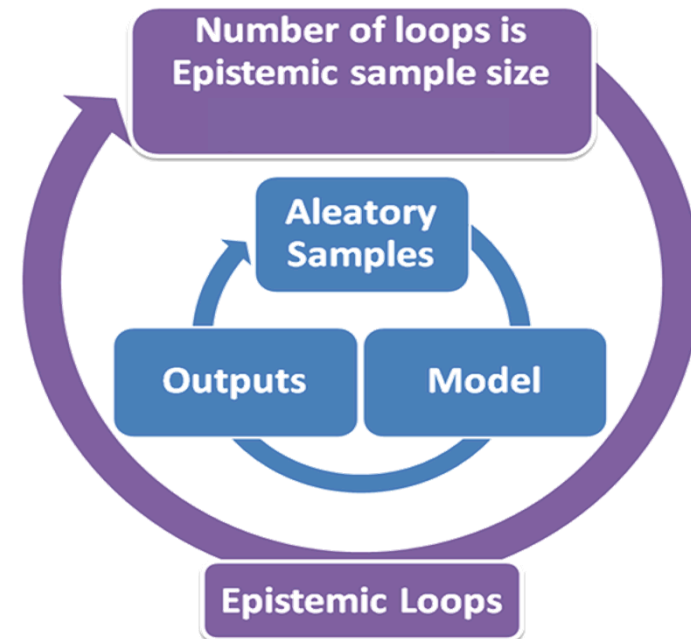


# Uncertainty representation in xLPR

- **Aleatory uncertainty**
  - Inherent randomness. Represented with probability distributions.
- **Epistemic uncertainty**
  - Uncertainty originated from lack of knowledge on a fixed quantity. Represented with probability distributions.
- Experts disagree on how to categorize certain inputs
- Inner aleatory loop
- **Outer epistemic loop**
  - Allows evaluation of epistemic (model) uncertainty.

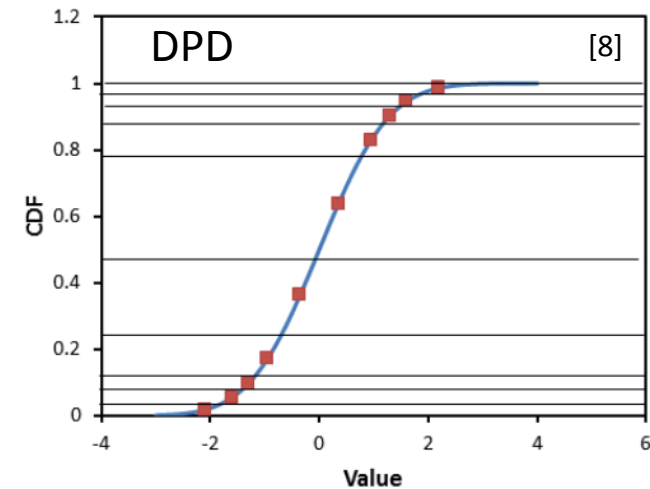
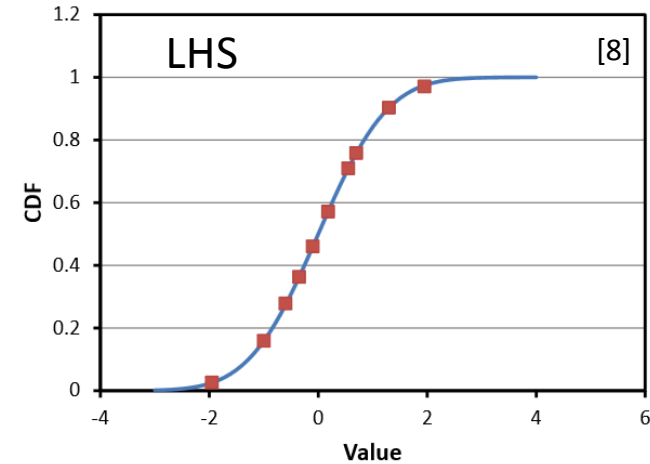
Aleatory (Irreducible)
<ul style="list-style-type: none"> <li>• Crack size</li> <li>• POD detection</li> <li>• Material properties</li> <li>• Crack growth parameters (Q/R,c,P)</li> </ul>

Epistemic (Lack of knowledge)
<ul style="list-style-type: none"> <li>• Loads</li> <li>• WRS</li> <li>• Crack growth (fweld)</li> <li>• Crack initiation parameters</li> <li>• POD parameters</li> </ul>



# xLPR V2.0 – Sampling strategy

- For each loop, the xLPR allows:
  - Simple random sampling (sometimes called Monte Carlo)
  - Latin Hypercube Sampling (LHS)
    - dense stratification of each input into equal probably intervals, then **random sample** in interval
  - Discrete Probability Distribution (DPD)
    - dense stratification of each input into equal probably intervals, then **use conditional mean** in interval
    - better multidimensional coverage than LHS – better if variables are important *conjointly* and a reasonable range of values (not as dense as LHS) is required/sufficient
  - Importance sampling applied to selected values

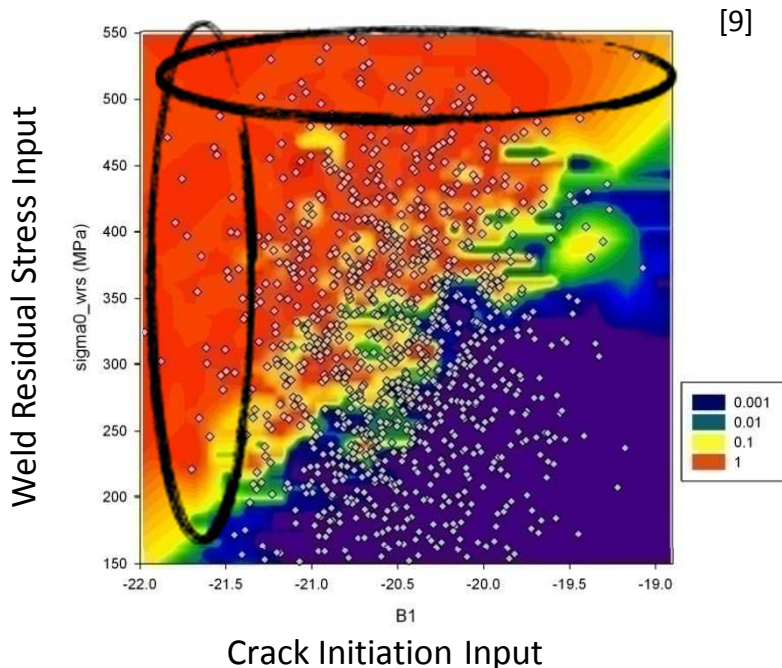


# xLPR V2.0 – Sampling strategy

- For each loop, the xLPR allows:
  - Importance sampling applied to selected values
    - Define regions to focus sampling on but reduce the weights applied to those results

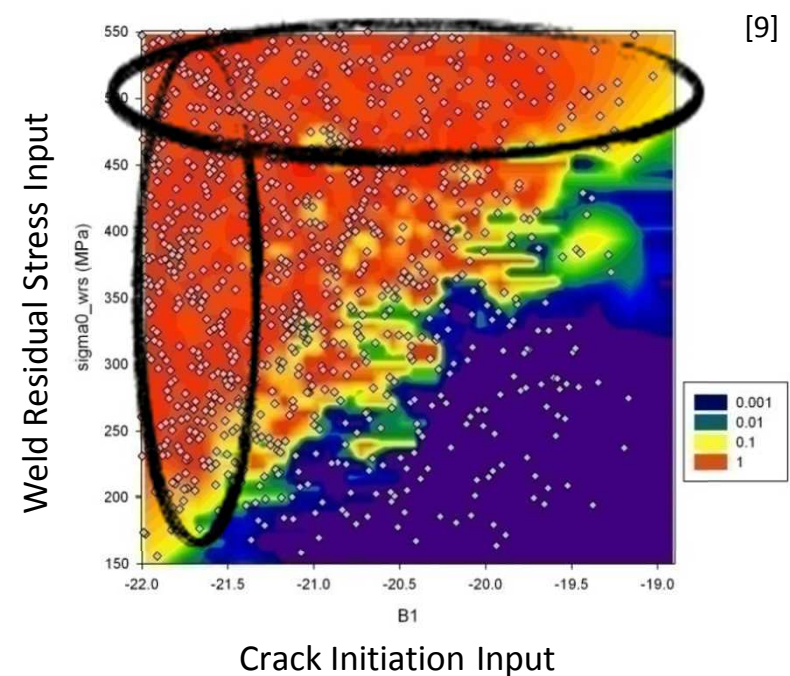
Areas poorly covered by sampling

Probability of rupture (50yr)



A lot more sampling in the critical regions

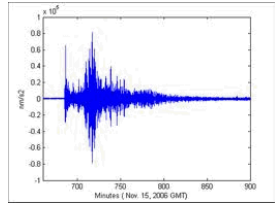
Probability of rupture (50yr)



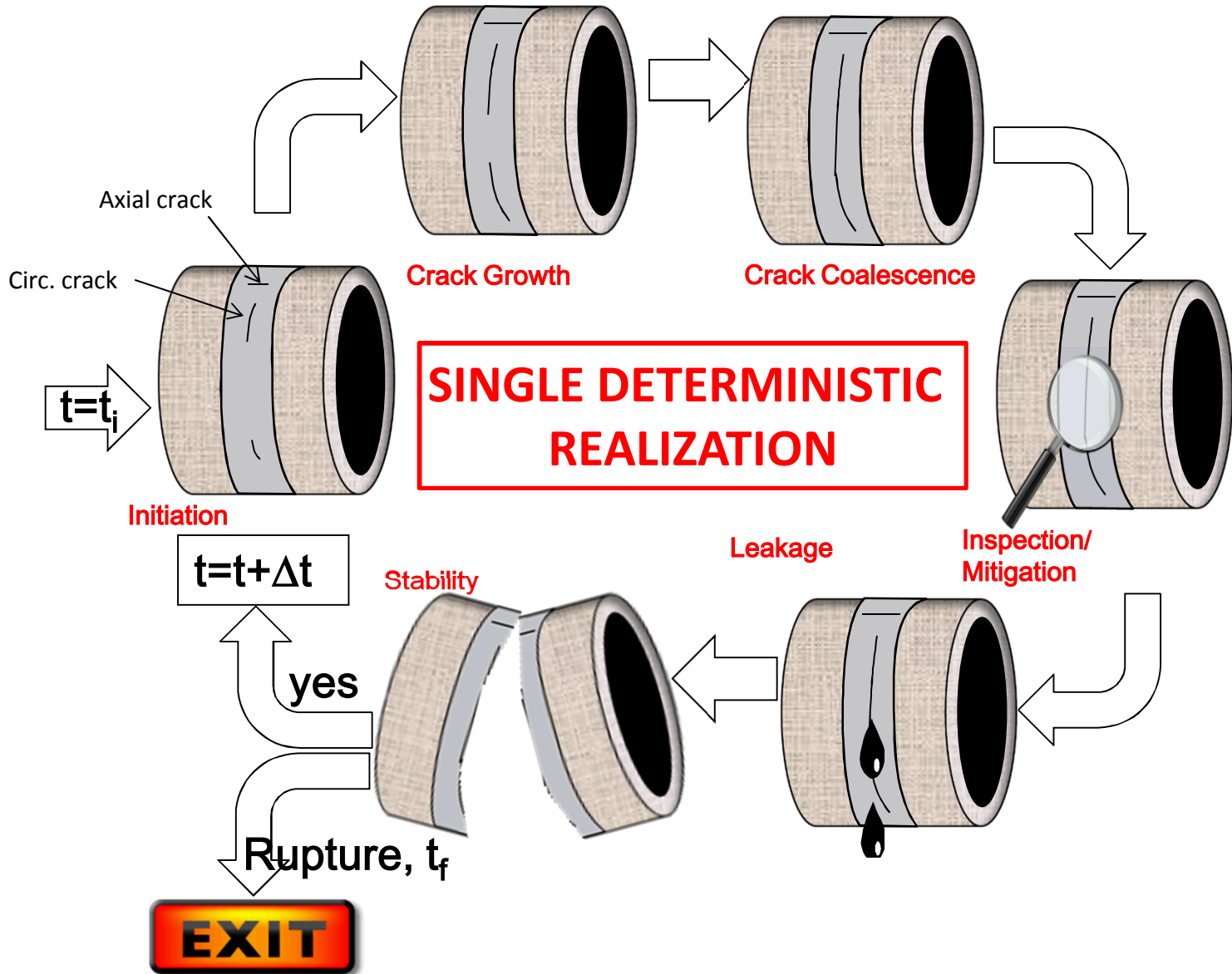
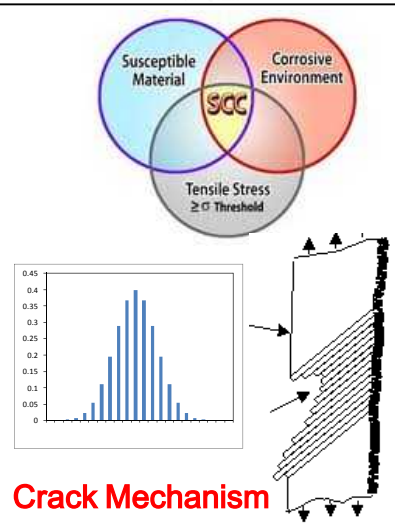
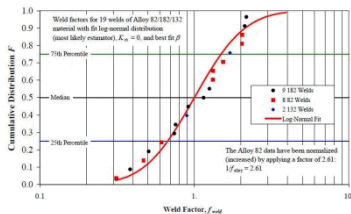
# xLPR V2.0 – Conceptual flow

## Deterministic Model Within Probabilistic Framework

### Loads

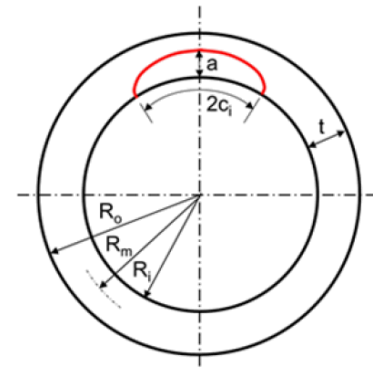


### Material Properties

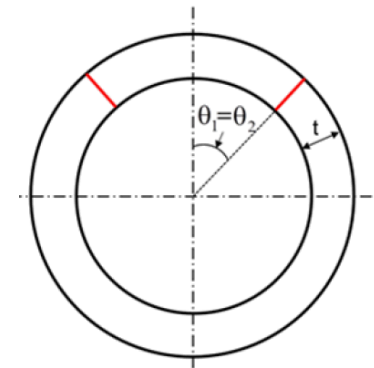


# Deterministic Model

- Must be realistic representation of **physical phenomena** *but* also fast enough to run  $>10^6$  realizations
- Key assumptions
  - Cracks can be either circumferential (circ.) or axial oriented cracks
  - Idealized crack shapes
  - No interaction between circ. and axial cracks
- Each deterministic model individually validated against available data (field data, lab data, other models, etc.)
- Probabilistic framework ties deterministic models together in a *modular* way and evolves cracks through time



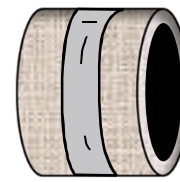
Ideal surface crack  
(SC)



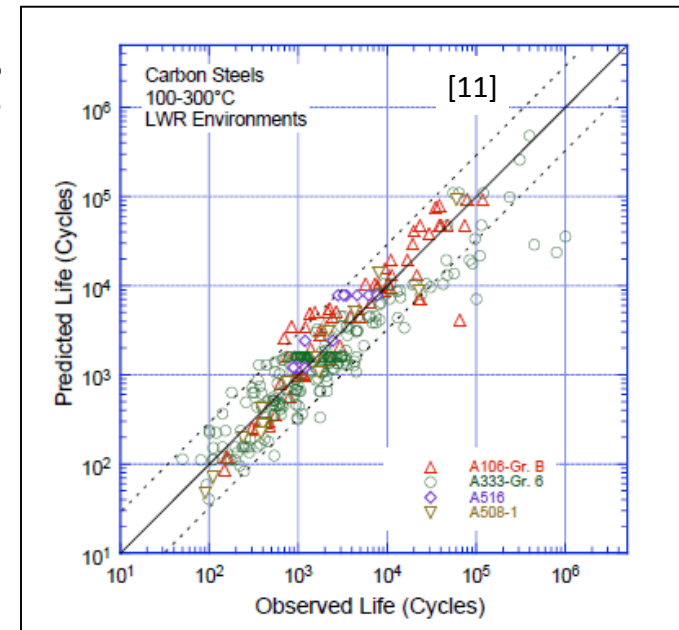
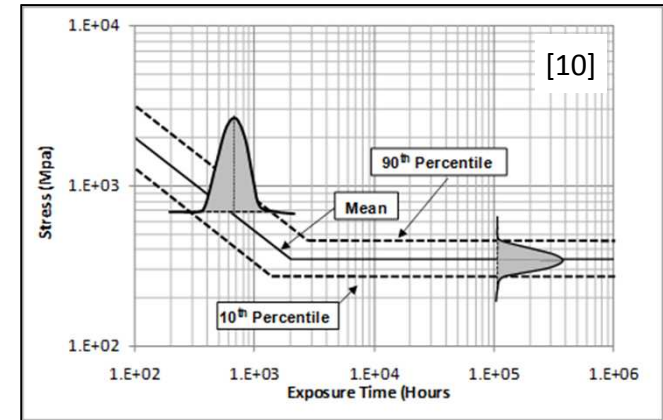
Ideal through wall  
crack (TWC)

# Deterministic Model

## Crack Initiation

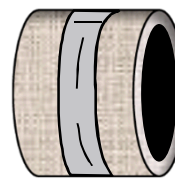


- PWSCC
  - 3 models available
  - Calibrated to field data
- Fatigue
- Initial Flaw (pre-existing)
- Flaw is initiated at engineering size



# Deterministic Model

## Crack Growth



- Loads – WRS, bending, axial, transients, etc.
- Stress intensity factors – “K”
  - Many solution methods available for ideal crack geometries
- K drives growth
  - General PWSCC form

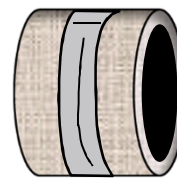
$$\dot{a}_{PWSCC} = \begin{cases} \alpha f_{comp} f_{flaw} e^{-\frac{Q_g}{R_{gas}} \left( \frac{1}{T} - \frac{1}{T_{ref}} \right)} (K_I - K_{th})^\beta & K_I > K_{th} \\ 0 & K_I \leq K_{th} \end{cases}$$

- General fatigue form

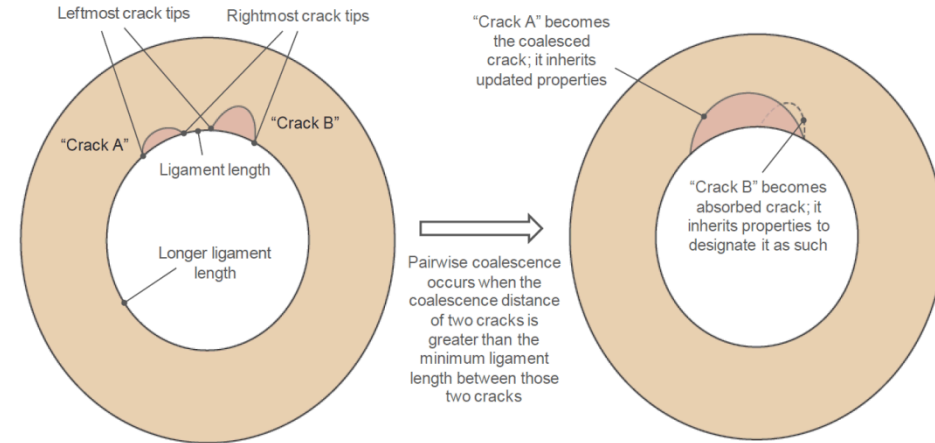
$$\dot{a}_{fatigue,i} = \frac{1}{\Delta t} \left[ \frac{da_i}{dN} \cdot N_{cyc,i} \right]$$

$$\frac{da_i}{dN} = C_{cstm} \tau_{r,i}^{p_{cstm}} \left( \frac{\Delta K_i}{(1 - a_{cstm} R_i)^{b_{cstm}}} \right)^{m_{cstm}}$$

# Deterministic Model Crack Coalescence

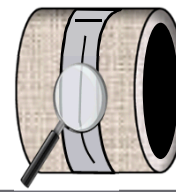


- Only applicable to circumferential cracks
- Cracks assumed to be in the same plane
- Rule based to determined if two cracks are close enough to interact

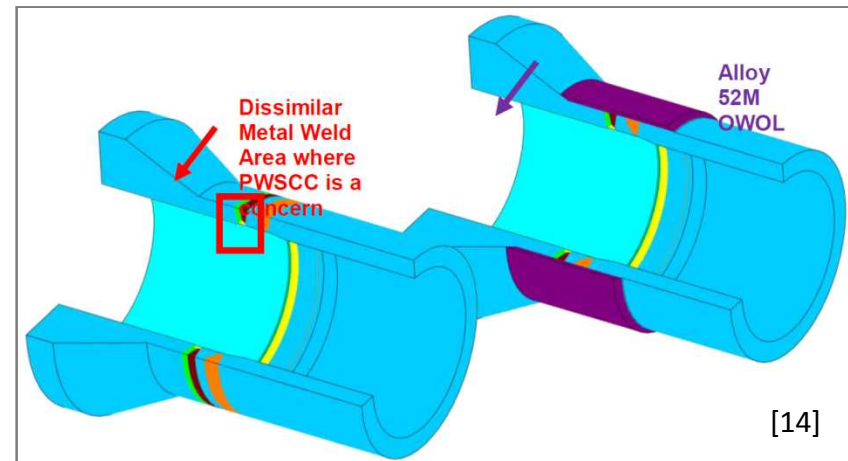
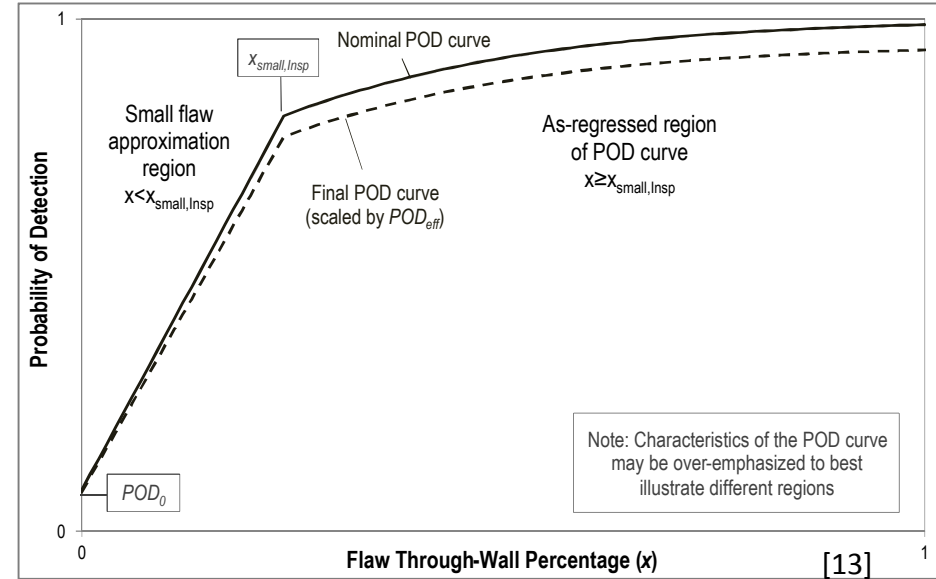


[12]

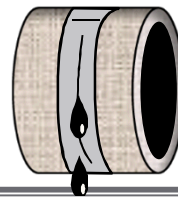
# Deterministic Model Inspection and Mitigation



- **Ultrasonic test inspection**
- **Given a flaw of certain depth:**
  - What is the probability of detection?
  - What is the “depth” evaluated from the inspection?
- **Repair weld if evaluated “depth” is > some threshold**
- **Mitigation**
  - **Stress/structural: Inlay, Onlay, MSIP**
  - **Chemistry: H2, Zinc**



# Deterministic Model Leak Detection



- For ideal shaped TWCs under given loads:
  - crack opening displacement (COD) obtained by analytical solutions that have been benchmarked against finite element analyses
  - COD → COA
- LEAPOR (leak rate preprocessor) generates look-up tables prior to running simulation

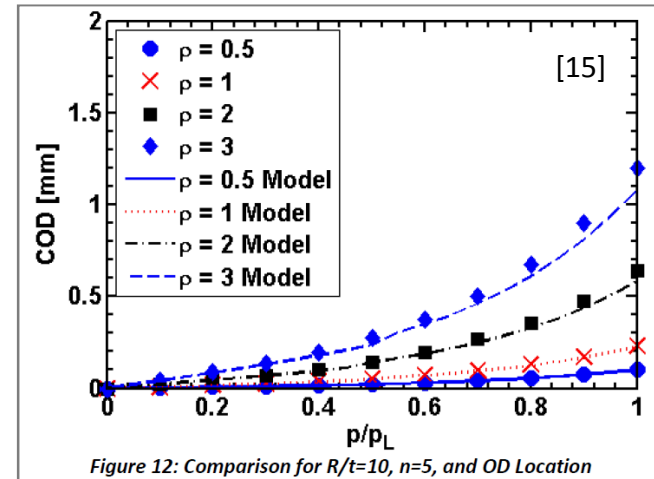
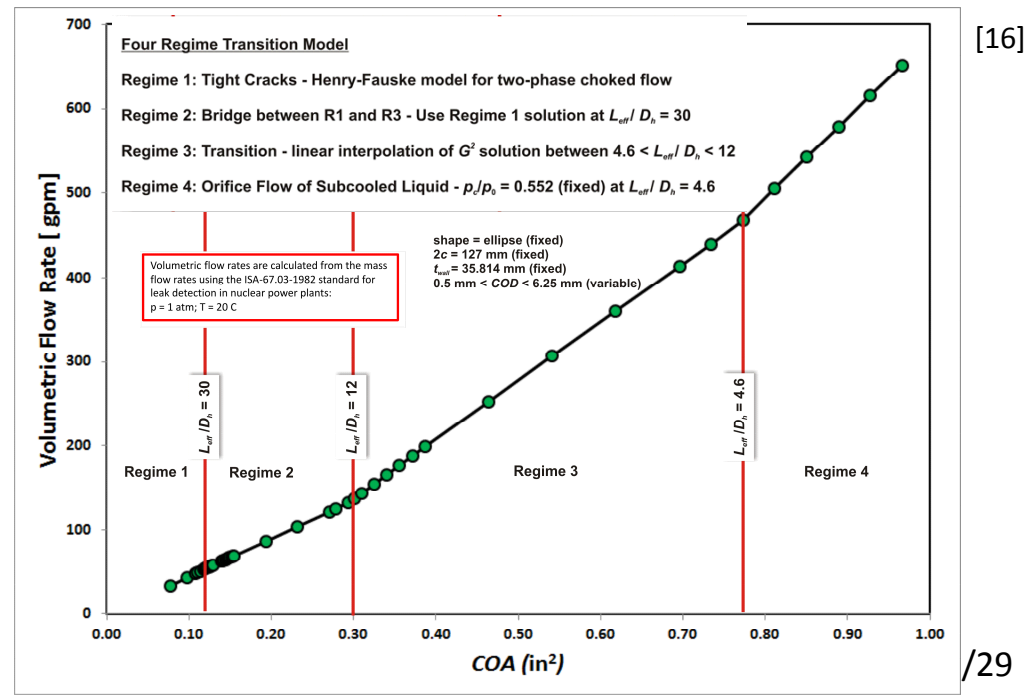


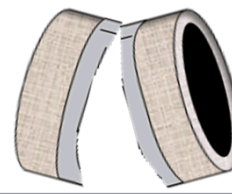
Figure 12: Comparison for  $R/t=10$ ,  $n=5$ , and OD Location



# Deterministic Model

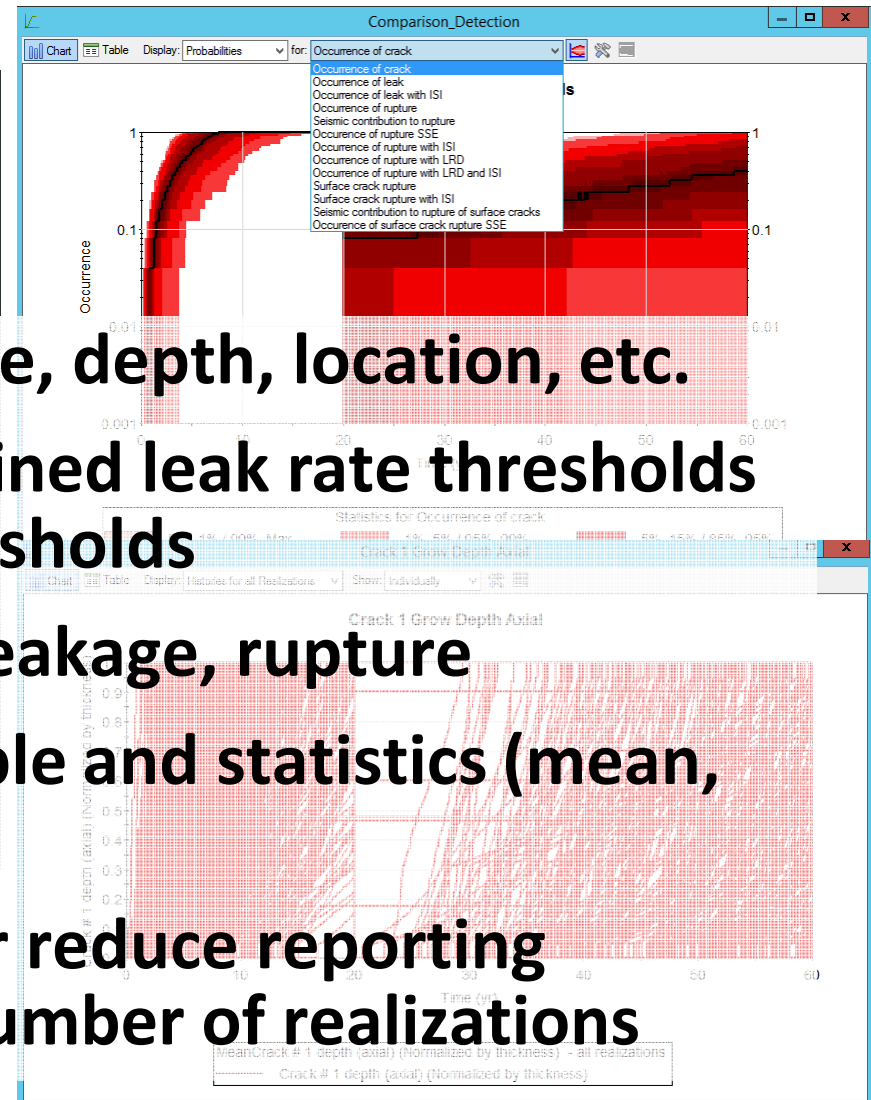
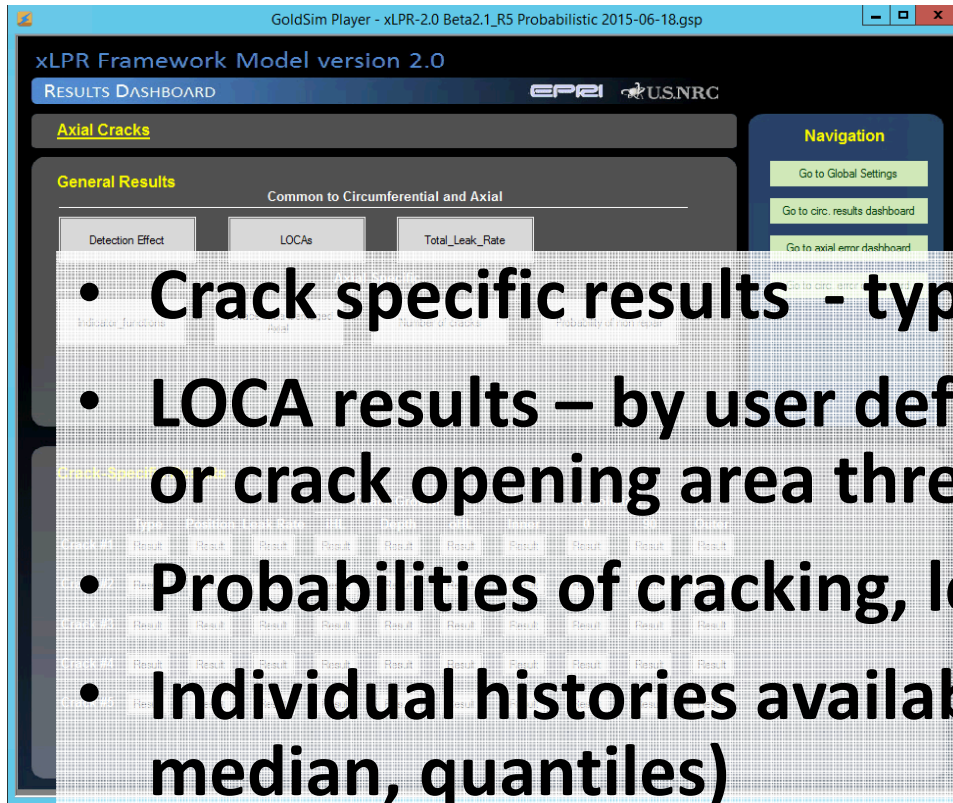
## Stability

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- **Loads on cracked weld are greater than the remaining section can maintain**
  - With and without Safe Shutdown Earthquake (SSE) loads
- **Circumferential cracks**
  - Surface Crack (SC) – Net Section Collapse
  - Through Wall Crack (TWC) – Net Section Collapse and/or elastic-plastic tearing instability
- **Axial cracks**
  - SC – limit load analysis in Ductile Fracture Handbook
  - TWC – limit load and elastic-plastic tearing instability

# Results Available from xLPR Runs



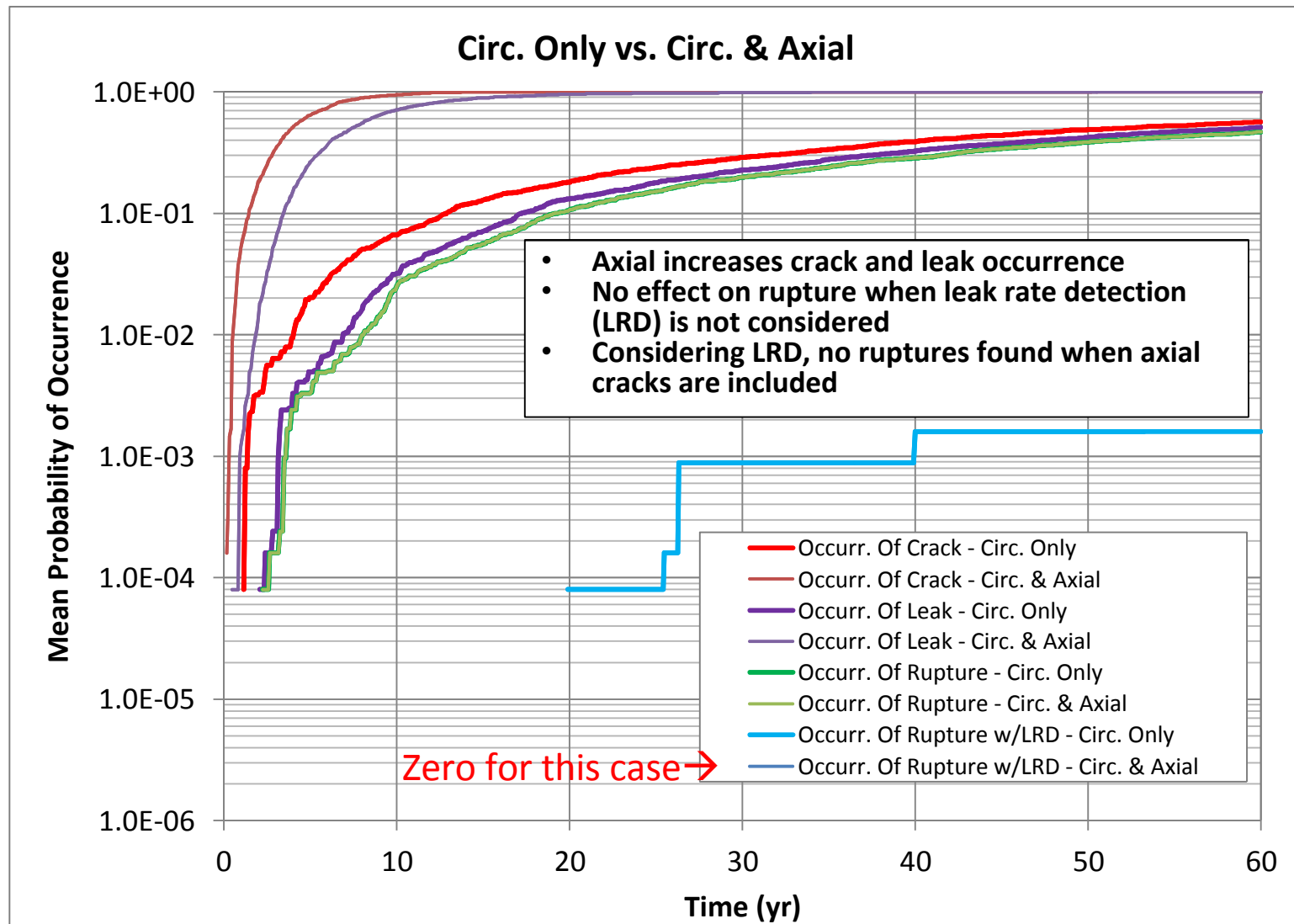
- Crack specific results - type, depth, location, etc.
- LOCA results – by user defined leak rate thresholds or crack opening area thresholds
- Probabilities of cracking, leakage, rupture
- Individual histories available and statistics (mean, median, quantiles)
- Can turn results off and/or reduce reporting frequency for very large number of realizations

# Some Example Results

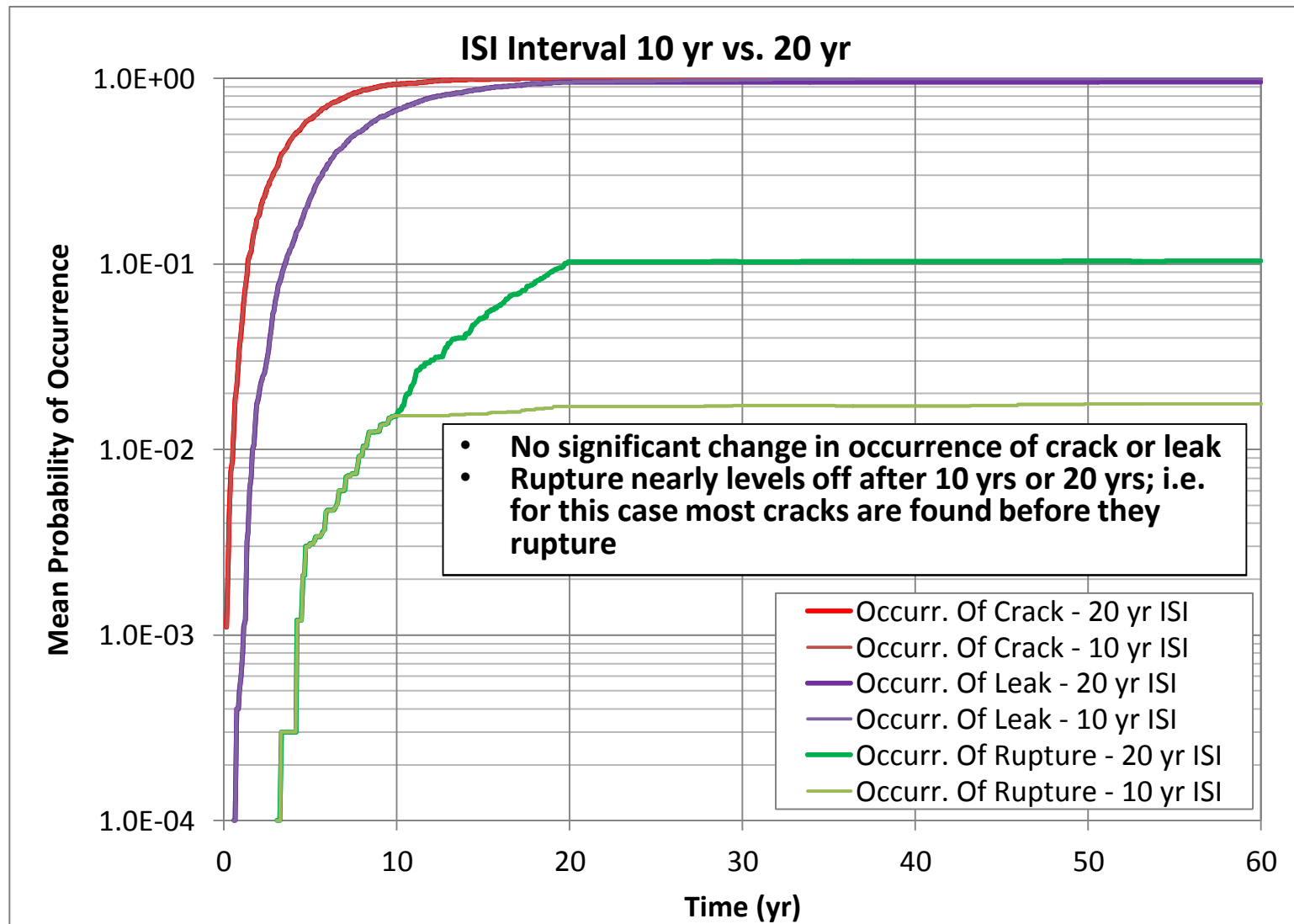
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- **The following results are meant to demonstrate different options available in the code and their effects on the important results.**
  - **Beta version of the xLPR V2.0 code – bugs may still exist**
  - **Not all inputs may be realistic – input databases still being created**
- **The results presented are based on a dissimilar metal weld for a reactor pressure vessel nozzle**
  - **Base metals - SA-508 and SA-182**
  - **Weld material – Inconel 182**
- **Same geometry, materials, loads (except transients), WRS, and sample size used for all the following demonstrations**

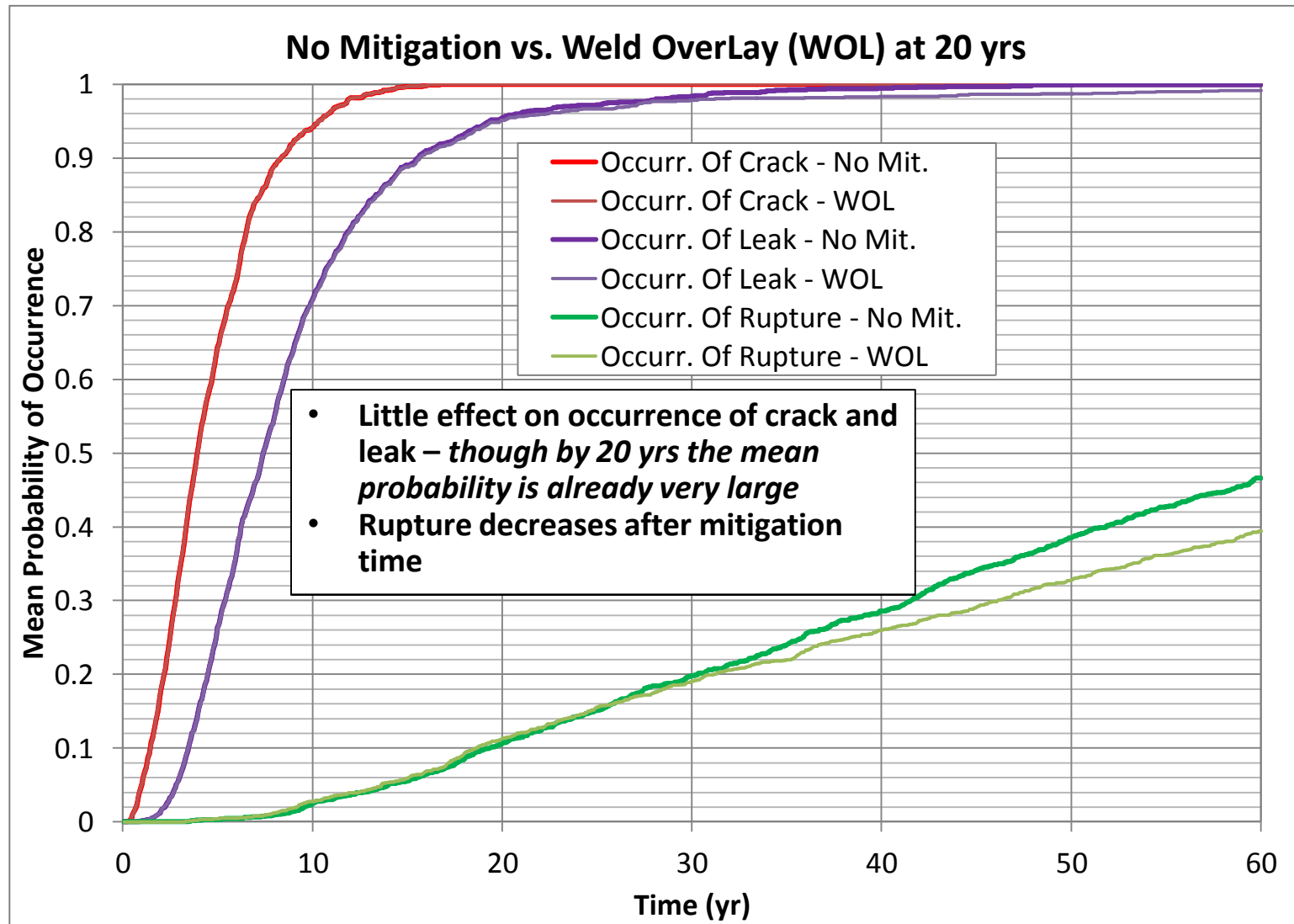
# Effect of Including Axial Cracks



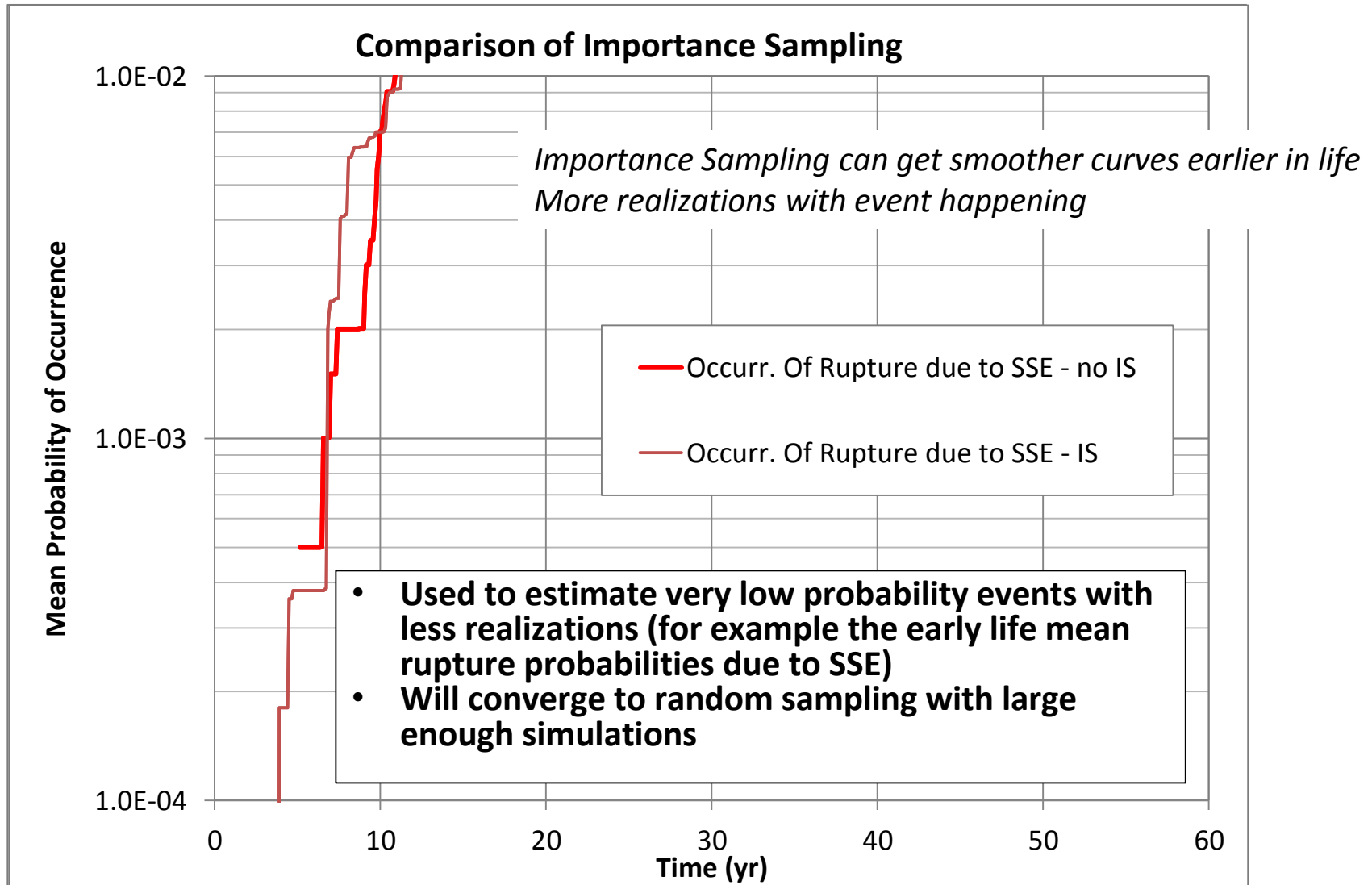
# Effect of In-Service Inspection (ISI) Interval



# Effect of Mechanical Mitigation

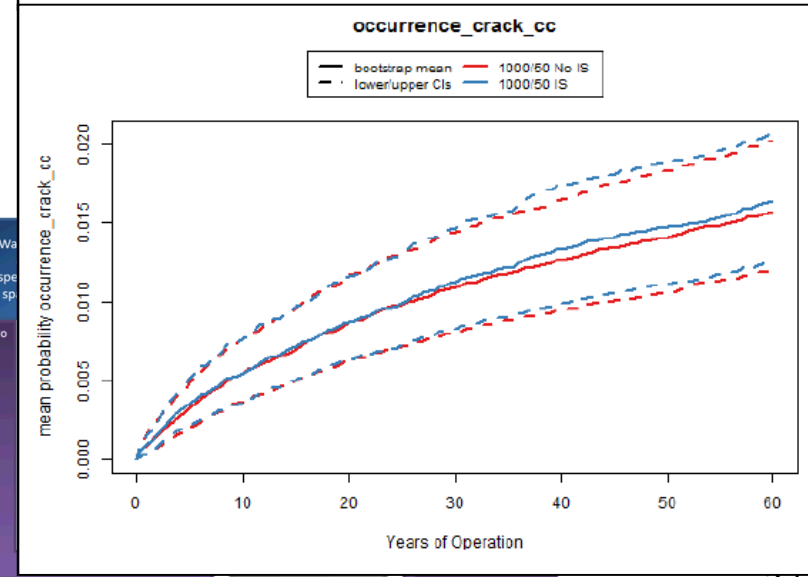
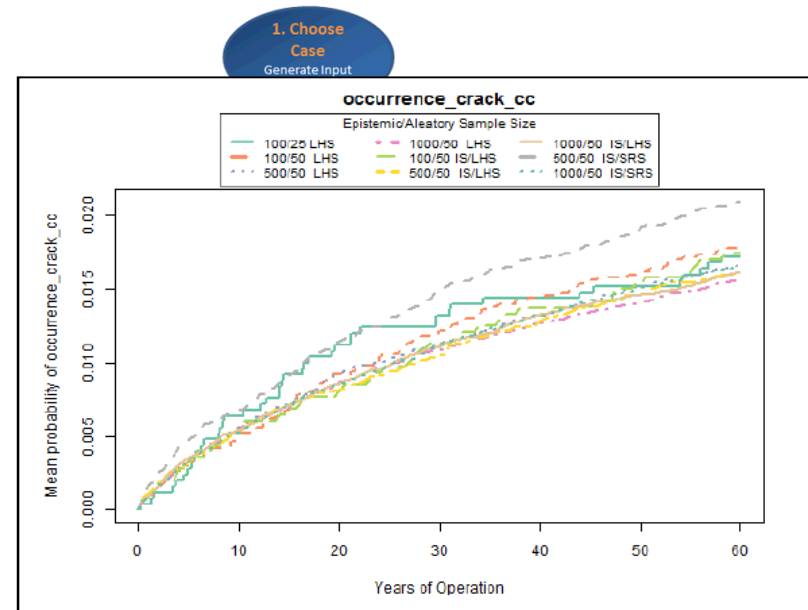
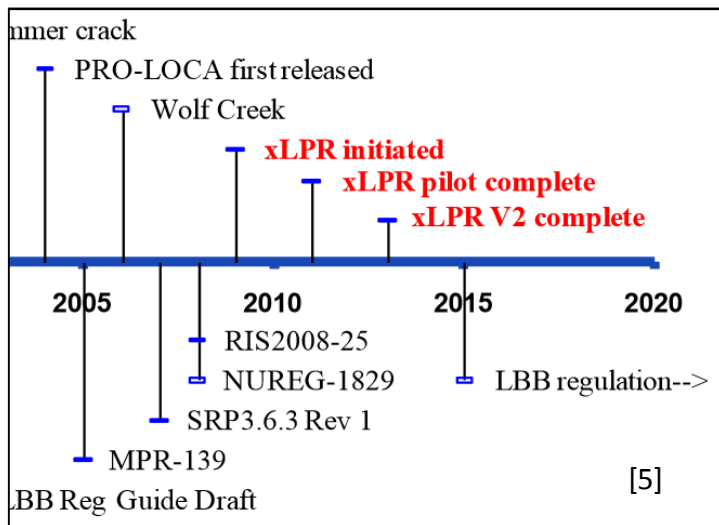


# Use of Importance Sampling (IS)



# Current Status

- Code under V&V
- Development of:
  - Scenario strategies
  - Probabilistic Fracture Mechanics code usage guidance



# Wrap Up

---

- **LBB Problem**
- **Probabilistic Approach**
- **Deterministic Models**
- **Some results**
- **Current Status**

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